



Application for United States Letters Patent  
for

Monolithic Optical Compensation Device For Improved Viewing Angle in  
Liquid Crystal Displays

by  
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1. REFERENCES

This is a continuation-in-part application of U.S. Patent Application, serial number 223,251, filed April 4, 1994, entitled "Optical Compensator for Improved Gray Scale Performance in Liquid Crystal Display," now U.S. Patent 5,504,603. In addition, U.S. Patent No. 5,196,953 and the following contemporaneously filed U.S. patent applications are hereby incorporated by reference: (i) "Inorganic Thin Film Compensator For Improved Gray Scale Performance in Twisted Nematic Liquid Crystal Displays" by William J. Gunning, III, Bruce K. Winker, Donald B. Taber, Paul H. Kobrin, James C. Beedy, and John P. Eblen, Jr.; and (ii) "Organic Polymer O-Plate Compensator For Improved Gray Scale Performance in Twisted Nematic Liquid Crystal Displays" by Bruce K. Winker, Hong-Son Ryang, Leslie F. Warren, Jr., and Charles Rosenblatt, Zili Li, and Young J. Chung. All referenced patents and patent applications are commonly assigned with this application.

## 2. BACKGROUND OF THE INVENTION

This invention is concerned with the design of liquid crystal displays (LCDs) and, more particularly, with techniques for maximizing the field of view of such displays by maintaining a high contrast ratio and minimal variance in relative gray levels over a wide range of viewing angles. These goals are achieved through the fabrication and manufacture of LCDs using a monolithic compensator device.

### 2.1 LCD Technology Overview

Liquid crystals are useful for electronic displays because polarized light traveling through a liquid crystal layer is affected by the layer's birefringence, which can be changed by the application of a voltage across the layer. By using this effect, the transmission or reflection of light from an external source, including ambient light, can be controlled with much less power than is required for the luminescent

3

1 materials used in other types of displays. As a result, liquid crystal displays are now commonly used in a  
2 wide variety of applications, such as, for example, digital watches, calculators, portable computers, and  
3 many other types of electronic equipment. These applications highlight some of the advantages of LCD  
4 technology including very long operational life in combination with very low weight and low power  
5 consumption.

6  
7 The information content in many liquid crystal displays is presented in the form of multiple rows of  
8 numerals or characters, which are generated by segmented electrodes deposited in a pattern on the display.  
9 The electrode segments are connected by individual leads to electronic driving circuitry. By applying a  
10 voltage to the appropriate combination of segments, the electronic driving circuitry controls the light  
11 transmitted through the segments.

12  
13 Graphic and television displays may be achieved by employing a matrix of pixels in the display  
14 which are connected by an X-Y sequential addressing scheme between two sets of perpendicular  
15 conductors. More advanced addressing schemes, applied predominantly to twisted nematic liquid crystal  
16 displays, use arrays of thin film transistors to control driving voltages at the individual pixels.

17  
18 Contrast and stability of relative gray scale intensities are important attributes in determining the  
19 quality of a liquid crystal display. The primary factor limiting the contrast achievable in a liquid crystal  
20 display is the amount of light which leaks through the display in the dark state. In addition, the contrast  
21 ratio of the liquid crystal device also depends on the viewing angle. The contrast ratio in a typical liquid  
22 crystal display is a maximum only within a narrow viewing angle centered about normal incidence and  
23 drops off as the angle of view is increased. This loss of contrast ratio is caused by light leaking through the  
24 black state pixel elements at large viewing angles. In color liquid crystal displays, such leakage also causes  
25 severe color shifts for both saturated and gray scale colors.

26  
27 The viewing zone of acceptable gray scale stability in a typical prior art twisted nematic liquid

1 crystal display is severely limited because, in addition to color shifts caused by dark state leakage, the  
2 optical anisotropy of the liquid crystal molecules results in large variations in gray level transmission, i.e., a  
3 shift in the brightness-voltage curve, as a function of viewing angle. The variation is often severe enough  
4 that, at extreme vertical angles, some of the gray levels reverse their transmission levels. These limitations  
5 are particularly important for applications requiring a very high quality display, such as in avionics, where  
6 viewing of cockpit displays from both pilot and copilot seating positions is important. Such high  
7 information content displays require that the relative gray level transmission be as invariant as possible  
8 with respect to viewing angle. It would be a significant improvement in the art to provide a liquid crystal  
9 display capable of presenting a high quality, high contrast image over a wide field of view.

10  
11 Figures 1A and 1B show a conventional normally, white, twisted nematic liquid crystal display 100  
12 including a polarizer 105, an analyzer 110 with a polarization axis perpendicular to that of the polarizer  
13 105, a light source 130, and a viewer 135.

14  
15 In the normally white configuration of Figures 1A and 1B, a "nonselect" area 115 (no applied  
16 voltage) appears light, while a "select" area 120 (those which are energized by an applied voltage) appear  
17 dark. In the select area 120 the liquid crystal molecules tend to tilt and rotate toward alignment with the  
18 applied electric field. If this alignment were perfectly homeotropic, all the liquid crystal molecules in the  
19 cell would be oriented with their long axes normal to the cell's major surface.

20  
21 Because the liquid crystals used for twisted nematic displays exhibit positive birefringence, this  
22 arrangement, known as the homeotropic configuration, would exhibit the optical symmetry of a positively  
23 birefringent C-plate. As is well known in the art, a C-plate is a uniaxial birefringent plate with its  
24 extraordinary axis (i.e., its optic or c-axis) perpendicular to the surface of the plate (parallel to the direction  
25 of normally incident light). In the select state the liquid crystal in a normally white display would thus  
26 appear isotropic to normally incident light, which would be blocked by the crossed polarizers.

One reason for the loss of contrast with increased viewing angle which occurs in a normally white display is that a homeotropic liquid crystal layer will not appear isotropic to off-normal light. Light propagating through the layer at off-normal angles appears in two modes due to the birefringence of the layer; a phase delay is introduced between those modes and increases with the incident angle of the light. This phase dependence on incidence angle introduces an ellipticity to the polarization state which is incompletely extinguished by the second polarizer, giving rise to light leakage. To correct for this effect, an optical compensating element must also have C-plate symmetry, but with negative birefringence ( $n_e < n_o$ ). Such a compensator will introduce a phase delay opposite in sign to the phase delay caused by the liquid crystal layer, thereby restoring the original polarization state and allowing light passing through energized areas of the layer to be blocked more completely by the output polarizer. C-plate compensation, however, does not impact the variation of gray scale with viewing angle, which is addressed by the present invention.

Figure 2 depicts the coordinate system which is used to describe the orientation of both liquid crystal and birefringent compensator optic axes. Light propagates toward the viewer 200 in the positive z direction 205 which, together with the x-axis 210 and the y-axis 215, form a right-handed coordinate system. Backlighting is provided, as indicated by the arrows 220, from the negative z direction. The polar tilt angle  $\Theta$  225 is defined as the angle between the liquid crystal's molecular optic axis  $\hat{c}$  230 and the x-y plane, measured from the x-y plane. The azimuthal or twist angle  $\Phi$  235 is measured from the x-axis to the projection 240 of the optic axis into the x-y plane.

## 2.2 Normally White Twisted Nematic LCDs

Figure 3 is a cross sectional schematic view of a prior art twisted nematic, transmissive type normally white liquid crystal display. The display includes a polarizer layer 300 and an analyzer layer 305, between which is positioned a liquid crystal layer 310, consisting of a liquid crystal material in the nematic phase.

6

1 It is convenient in describing the orientation of various compensation elements of the display to  
2 refer to a normal axis perpendicular to the display, which is depicted by a dashed line 370. The polarizer  
3 300 (with a polarization direction in the plane of the drawing 315) and the analyzer 305 (with a  
4 polarization direction into the plane of the drawing 320) are oriented with their polarization directions at  
5 90° to one another, as is the case for a normally white display. (A polarizer 300 and an analyzer 305 both  
6 polarize electromagnetic fields. Typically, however, the term 'polarizer' refers to a polarizer element that  
7 is closest the source of light while the term 'analyzer' refers to a polarizer element that is closest the viewer  
8 of the LCD.) A first transparent electrode 325 and a second transparent electrode 330 are positioned  
9 adjacent to opposite surfaces of the liquid crystal layer 310 so that a voltage can be applied, by means of a  
10 voltage source 335, across the liquid crystal layer. The liquid crystal layer is in addition sandwiched  
11 between a pair of glass plates 340 and 345. As is explained below, the inner surfaces of the glass plates  
12 340 and 345, which are proximate to the liquid crystal layer 310, can be physically or chemically treated to  
13 affect the desired liquid crystal orientation, as by buffing.

14  
15 As is well known in the LCD art (see, e.g., Kahn, "The Molecular Physics of Liquid-Crystal  
16 Devices," Physics Today, pp. 68-74, May 1982), when the material of the liquid crystal layer 310 is in the  
17 nematic phase and the inner surfaces of the plates 340 and 345 (the surfaces adjacent to the layer 310) are  
18 coated with a surface treatment for aligning the liquid crystal such as polyimide, buffed, and oriented with  
19 their buffed directions perpendicular, the director of the liquid crystal material, absent any applied electrical  
20 voltage, will tend to align with the buffed direction (known as the "rub direction") in the regions of the  
21 layer proximate each of the plates 340 and 345. Furthermore, the director will twist smoothly with respect  
22 to the normal axis through an angle of 90° along a path in the layer 310 from the first major surface  
23 adjacent to the plate 340 (i.e., at the 310/340 interface) to the second major surface adjacent to the plate  
24 345 (i.e., at the 310/345 interface).

25  
26 In the absence of an applied electric field the direction of polarization of incoming polarized light  
27 will be rotated by 90° in traveling through the liquid crystal layer. When the glass plates and the liquid

1 crystal layer are placed between crossed polarizers, such as the polarizer 300 and the analyzer 305, light  
2 polarized by the polarizer and traversing the display, as exemplified by the light ray 350, will thus be  
3 aligned with the polarization direction of the analyzer 320 and therefore will pass through the analyzer.

4  
5 When a sufficient voltage is applied to the electrodes 325 and 330, however, the applied electric  
6 field causes the director of the liquid crystal material to tend to align parallel to the field. With the liquid  
7 crystal material in this state, light passed by the polarizer 300, as illustrated by the light ray 355, will be  
8 extinguished by the analyzer 305. Thus, an energized pair of electrodes will produce a dark region in the  
9 display, while light passing through regions of the display which are not subject to an applied field will  
10 produce illuminated regions. As is well known in the LCD display art, an appropriate pattern of electrodes,  
11 activated in selected combinations, can be utilized in this manner to display alphanumeric or graphic  
12 information. As explained further below, one or more compensator layers, such as the layers 360 and 365,  
13 may be included in the display to improve the quality of the display.

### 14 15 2.3 Normally White Twisted Nematic LCD Characteristics

16

17 Figure 4 shows a calculated plot of liquid crystal director tilt as a function of position in a liquid  
18 crystal layer (where the cell gap has been normalized to unity) in a 90° twisted nematic cell. Typical  
19 distributions for molecular tilt angles when no voltage is applied (curve 400), under a typical select state  
20 voltage (curve 405), and under the application of several intermediate voltages chosen to yield linearly  
21 spaced gray levels (curves 410, 415, 420, 425, 430, and 435) are shown.

22  
23 Figure 5 is a related plot for the same cell depicting the calculated twist angle of the liquid crystal  
24 molecules as a function of position in the cell. When there is no applied voltage, the twist is distributed  
25 evenly throughout the cell (straight line curve 500). Under a fully select state voltage, the twist angles are  
26 distributed as shown by the external, S-shaped curve 505. The twist distributions for gray levels are shown  
27 by the intermediate curves between the two curves 500 and 505.



As illustrated by Figures 4 and 5, when the fully selected voltage is applied nearly all of the twist experienced by the liquid crystal molecules, and a substantial portion of the tilt, occurs in the central region of the cell. Because of this phenomena, the continuous variation of molecular orientation within the cell can be separated into three regions, each of which is characterized by its own optical symmetry. Thus, the central regions 440 (Figure 4) and 510 (Figure 5) can be considered as nominally homeotropic in the fully selected state, approximating the properties of a C-plate. The regions 445 and 450 (Figure 4) and 515 and 520 (Figure 5), near each surface of the cell, behave as A-plates, each with its extraordinary axis aligned with the rub direction of the proximate substrate. Because there is essentially no twist in the molecules in the regions 445, 450, 515, and 520, the molecules are essentially aligned with the respective rub directions on either side of the liquid crystal layer. In addition, because the twist angle of the molecules in the regions 445 and 515 tends to be perpendicular to the twist angle of the molecules in the regions 450 and 520, the effect of these two regions on light traveling through the cell tends to be canceled, leaving the middle C-plate region to exert the dominant influence.

### 2.3(a) C-Plate Compensation

As is well known in the art, a negative C-plate compensator is designed to correct for the angle dependent phase shift introduced by propagation through the central, approximately C-plate region of a LCD cell. Such a compensator is effective to the extent that the optical symmetry of the central region dominates the selected state of the liquid crystal cell, that is, the extent to which the molecules align with the applied field. This implies that negative C-plate compensation will work best when strong fields are used for the energized state as this makes the homeotropic approximation more nearly correct. The use of a C-plate has been demonstrated to significantly reduce the leakage of the dark state over an extended field of view, thus improving contrast and reducing color desaturation.

## 2.3(b) Gray Scale Stability

While the use of a C-plate compensator may be used to eliminate color desaturation, it does not improve gray scale stability. The problem of maintaining constant gray scale luminance differences over the field of view relates substantially to the brightness level changes for levels assigned between the select (black for a normally white display) and nonselect (white for a normally white display) states. This phenomenon is generally depicted using transmission, or brightness, versus voltage (BV) electro-optic response curves for a display to which eight gray levels are assigned, from level 0 (the select black state) to level 7 (the nonselect white state). Gray levels between 0 and 7 are chosen by assigning them a set of voltages spaced linearly in brightness along the BV curve between the select and nonselect voltages.

Figure 6 is a plot of calculated BV (transmission versus drive voltage) curves for a normally white, 90° twisted nematic display as the horizontal viewing angle varies from 0° to 40° in 10° increments while the vertical viewing angle remains fixed at 0°. (The change in the BV curves with horizontal angle is, to first order, independent of whether the horizontal deviation is to the left or right.) Note that the regions of each curve over which gray levels would be selected almost overlies one another for the various horizontal angles. This means that gray levels chosen to be linearly spaced at zero degrees would remain very nearly linear at even high horizontal viewing angles.

The gray scale stability problem appears most predominantly when the vertical viewing angle varies. This is illustrated in Figure 7, which shows a series of BV curves for a normally white, 90° twisted nematic display as the vertical viewing angle varies from -10° to +30° while the horizontal viewing angle remains fixed at 0°. It can be observed that for angles below 0° (measured from the normal) the BV curves shift to the right (higher voltage), and fall monotonically from their maximum but fail to reach zero.

For angles above normal, the curves shift to the left and develop a rebound after an initial minimum. These effects can be explained by considering the perspectives of viewers looking at the display

1 from above, at, and below normal, as shown in Figure 8. The critical feature to note is the relationship  
2 between the light traveling towards the viewer and the average liquid crystal director tilt at the center of a  
3 cell as voltage across the cell is increased.

4  
5 For instance, as the voltage across a cell is increased, the average liquid crystal director in the  
6 center of the cell tilts from a parallel (with respect to the polarizer 300 and analyzer 305) orientation 815  
7 toward a homeotropic one 825. For the viewer at normal incidence 800, retardation is highest at the  
8 nonselect state voltage and lowest at the select state voltage. When the anisotropy is zero, the polarization  
9 state of the light is unchanged and it is blocked by the analyzer. Thus, the viewer sees a monotonic  
10 decrease in brightness to zero with increasing voltage.

11  
12 Now consider the case of a positive vertical viewing direction (viewer above normal incidence  
13 805). At some intermediate voltage the average director 820 points toward the viewer and the retardation is  
14 minimal. Here the viewer sees a brightness with voltage that initially decreases toward a minimum, at the  
15 point of minimal retardation, and then increases.

16  
17 For the negative vertical viewing direction (viewer below normal incidence 810), the average  
18 director always presents a large anisotropy to a light ray, even at the highest voltage. The viewer therefore  
19 sees a monotonic decrease in brightness. Furthermore, the average liquid crystal director is always oriented  
20 at a larger angle with respect to the light ray for the below normal viewer 810 than it is for the normal  
21 incidence viewer 800. Therefore the anisotropy is greater and the brightness level is always higher in the  
22 negative vertical viewing direction than it is at normal incidence.

23  
24 This dependency of an LCD's brightness versus viewing angle, has a profound impact on gray  
25 scale stability. In particular, the variation in gray level luminance versus vertical viewing angle can be  
26 extreme. (Note that a voltage chosen to yield a 50% gray level on the 0° curve in Figure 7 yields a dark  
27 state on the +30° curve and approaches a fully white state at -10°.)

### 2.3(c) O-Plate Gray Scale Compensation

To eliminate reversal of gray levels and improve gray scale stability, a birefringent O-plate compensator can be used. The O-plate compensator principle, as described in U.S. Patent Application 223,251 utilizes a positive birefringent material with its principal optic axis oriented at a substantially oblique angle with respect to the plane of the display (hence the term "O-plate"). "Substantially oblique" implies an angle appreciably greater than  $0^\circ$  and less than  $90^\circ$ . O-plates have been utilized, for example, with angles relative to the plane of the display between  $30^\circ$  and  $60^\circ$ , typically at  $45^\circ$ . Moreover, O-plates with either uniaxial or biaxial materials can be used. O-plate compensators can be placed in a variety of locations between a LCD's polarizer layer and analyzer layer.

In general, O-plate compensators may also include A-plates and/or negative C-plates as well as O-plates. As is well known in the art, an A-plate is a birefringent layer with its extraordinary axis (i.e., its c-axis) oriented parallel to the surface of the layer. Its a-axis is thus oriented normal to the surface (parallel to the direction of normally incident light), leading to its designation as an A-plate. A-plates may be fabricated by the use of uniaxially stretched polymer films, such as polyvinyl alcohol, or other suitably oriented organic birefringent materials.

A C-plate is a uniaxial birefringent layer with its extraordinary axis oriented perpendicular to the surface of the layer (parallel to the direction of normally incident light). Negatively birefringent C-plates may be fabricated by the use of uniaxially compressed polymers (See, e.g., Clerc, U.S. Patent No. 4,701,028), stretched polymer films, or by the use of physical vapor deposited inorganic thin films (See, e.g., Yeh, U.S. Patent No. 5,196,953), for example.

Oblique deposition of a thin film by physical vapor deposition is known to produce a film having birefringent properties (see, e.g., Motohiro and Taga, "Thin Film Retardation Plate by Oblique Deposition," Appl. Opt., Vol. 28, No. 3, pp. 2466-2482, 1989). By further exploiting the tilted orientation

1 of the symmetry axis, the Motohiro process can be refined or enhanced to fabricate O-plates. Such  
2 components are by their nature biaxial. Their growth characteristics generate a microscopic columnar  
3 structure. The angles of the columns are tipped toward the direction of the arrival of a vapor stream. A  
4 deposition angle (measured from normal) of  $76^\circ$ , for example, results in a column angle of approximately  
5  $45^\circ$ . The columns develop an elliptical cross section as the result of shadowing. This elliptical cross  
6 section gives rise to the biaxial character of the films. The birefringence, in magnitude and symmetry, is  
7 entirely attributable to the film microstructure and is referred to as form birefringence. These phenomena  
8 in thin films have been extensively studied and described by Macleod ("Structure-Related Optical  
9 Properties of Thin Films," J. Vac. Sci. Technol. A, Vol. 4, No. 3, pp. 418-422, 1986).

10  
11 Uniaxial O-plate components similarly offer numerous solutions. These may be fabricated by the  
12 use of suitably oriented organic birefringent materials. Those skilled in the art will recognize other means  
13 for fabricating both uniaxial and biaxial O-plates.

14  
15 Figures 9 and 10 show one effect that an O-plate compensator layer can have on a normally white  
16 twisted nematic display. Figure 9 shows the O-plate compensator layer's effect on the electro-optic  
17 response of the display at various horizontal viewing angles while Figure 10 shows the O-plate  
18 compensator layer's effect on the display's vertical viewing angle. In this particular embodiment, one A-  
19 plate layer is positioned adjacent to the liquid crystal layer on both sides of the liquid crystal cell. An O-  
20 plate layer is disposed between the polarizer layer and the A-plate/liquid crystal/A-plate stack. The  
21 variation in the BV curves versus both horizontal and vertical viewing angles are greatly reduced relative to  
22 the uncompensated case shown in Figures 6 and 7.

23  
24 Elimination of gray scale reversal by the use of an O-plate compensator layer occurs in the  
25 following manner. In the positive vertical viewing direction, the retardation of the O-plate increases with  
26 viewing angle and tends to offset the decreasing retardation of the liquid crystal layer. When the viewer is  
27 looking down the axis of the average liquid crystal director, the presence of the O-plate prevents the layers

1 between the two polarizers from appearing isotropic. Thus the rebound in the BV curve, shown in Figure  
2 7, is reduced and moved to higher voltages outside of the gray scale voltage range as shown in Figure 10

3  
4 In the negative vertical viewing direction, the combination of an O-plate and an A-plate with their  
5 optic axes nominally at right angles tends to exhibit birefringence characteristics similar to that of a  
6 negative birefringence retarder with its optic axis oriented perpendicular to the plane containing the axes of  
7 the O-plate and A-plate. The direction of this retarder axis is nominally parallel to the orientation of the  
8 average liquid crystal in the central region of the cell when it is driven at a voltage between select and  
9 nonselect states. Thus, the presence of an O-plate oriented in this manner tends to cancel the birefringence  
10 of the liquid crystal layer, pulling the BV curve down, or equivalently, moving it toward the direction of  
11 lower voltages (i.e., left). A similar effect occurs in the positive and negative horizontal viewing directions  
12 as well.

13  
14 The overall effect of introducing an O-plate compensator in this manner is to eliminate large  
15 rebounds in the gray scale voltage region and reduce the left-to-right shift in the BV curves as the viewing  
16 angle is varied from negative to positive vertical angles.

17  
18 The orientations of the compensator optic axes can be carefully chosen so that the combined  
19 retardation effects cancel each other in the normal incidence viewing direction as well as minimize rebounds  
20 in the horizontal viewing direction. Combinations of more than one O-plate can be used as long as their  
21 orientations satisfy these requirements. Furthermore, negative C-plates can, for certain configurations,  
22 increase the contrast ratio at large fields of view, occasionally with some decrease in gray scale stability.

#### 23 24 2.3(d) O-Plate Technology

25

26 The liquid crystal layer, the compensator layer(s), the polarizer layer, and the analyzer layer may  
27 assume a variety of orientations relative to one another in a liquid crystal display. Some of the possible

configurations which have been considered, and set out in U.S. Patent Application No. 223,251 are repeated in Table 1; where 'A' represents an A-plate, 'C' represents a C-plate, 'O' represents an O-plate, 'LC' represents the liquid crystal, and 'OxO' represents crossed O-plates. Crossed O-plates are adjacent O-plates with their azimuthal angles  $\Phi$  235 nominally crossed, one oriented between  $0^\circ$  and  $90^\circ$ ; and the second oriented between  $90^\circ$  and  $180^\circ$ .

Table 1. Liquid Crystal Display Elements

← Toward Rear (Polarizer Side)			Toward Front (Analyzer Side) →		
		O	A	LC	
		A	O	LC	
			O	LC	O
	A	O	A	LC	A
		O	A	LC	A
	O	A	C	LC	
		OxO	A	LC	
	A	OxO	A	LC	
			A	LC	OxO
A	O	A	C	LC	A
		A	O	LC	O
	A	O	C	LC	C
	A	O	C	LC	C
	C	A	O	LC	O
					A
					C

The projections of the principal axes onto the plane of the display with respect to the liquid crystal director can vary with the embodiment. In some cases, for example with two O-plates, the O-plate axis projections are at  $45^\circ$  with respect to the average liquid crystal director, while in others, the O-plate axis projection is parallel with that of the liquid crystal director.

1           Crossed O-plate (OxO) designs that are further compensated with A-plates provide additional  
2 design flexibility. The choice of A-plate value is not critical as such designs can be adjusted by varying the  
3 relative orientations of the A-plates. Thus, it is possible to generate desired solutions with commercially  
4 available A-plate retardation values.

5  
6           The flexibility which an O-plate compensation scheme offers the display designer allows tailoring  
7 of performance to specific display product requirements. It is possible, for example, with simple  
8 configuration and parameter modifications to achieve isocontrast optimized for left or right viewing,  
9 isocontrast optimized for extreme vertical angle viewing, or isocontrast optimized for viewing at both large  
10 left and right angles above normal viewing. It is also possible to adjust the configuration and parameters to  
11 improve both the contrast and gray scale stability over a specified field of view, or to further optimize one  
12 at the expense of the other. Furthermore, a negatively birefringent A-plate may be substituted for a  
13 positively birefringent A plate. In this case, the negatively birefringent A-plate would be oriented with its  
14 extraordinary axis perpendicular to the orientation appropriate for a positively birefringent A-plate. As  
15 would be understood by one skilled in the art of liquid crystal display design, additional changes would also  
16 be required in the other components of the compensator to optimize performance when a negative A-plate is  
17 used.

## 18 19   2.4   Summary

20  
21           When viewed directly, a twisted nematic liquid crystal display provides high quality output, but at  
22 large viewing angles the image tends to degrade and exhibit poor contrast and gray scale nonuniformity.  
23 This occurs because the phase retardation effect of the liquid crystal material on light passing through it  
24 inherently varies with the inclination angle of the light, leading to a lower quality image at large viewing  
25 angles. By introducing one or more optical compensating elements in conjunction with the liquid crystal  
26 cell, however, it is possible to substantially correct for the undesirable angular effects and thereby maintain  
27 higher contrast and stable relative gray scale intensities at larger viewing angles than otherwise possible.



### 3. SUMMARY OF THE INVENTION

A monolithic O-plate optical compensator device, in accordance with the invention, comprises a plurality of thin-film compensation layers which are deposited on a single substrate. As used herein, the term "monolithic" is meant to imply that the O-plate and other thin-film compensator layers are formed by depositing (e.g., via solvent casting or vacuum deposition) one layer on top of another layer; with or without the use of surface modification treatments such as adhesion layers, alignment layers, and the like.

### 4. BRIEF DESCRIPTION OF DRAWINGS

Figure 1A and 1B shows, in overview, the operation of a normally white, 90° twisted nematic liquid crystal display.

Figure 2 depicts the coordinate system that is used to specify component orientations in the description of this invention.

Figure 3 is a cross sectional schematic view of a 90° twisted nematic, transmissive type normally white liquid crystal display.

Figure 4 is a plot of the tilt angle of the director (in degrees along the vertical axis) as a function of position (as a fraction of the depth along the horizontal axis) in a 90° twisted nematic liquid crystal cell.

Figure 5 is a related plot for the cell shown in Figure 4, depicting the twist angle of the liquid crystal molecules as a function of their position in the cell.

Figure 6 is a plot of calculated brightness vs. voltage (BV) electro-optic curves at a variety of horizontal viewing directions for a typical twisted nematic display without the benefit of O-plate gray scale

1 compensation.

2  
3 Figure 7 is a plot of calculated brightness vs. voltage (BV) electro-optic curves at a variety of  
4 vertical viewing directions for a typical twisted nematic display without the benefit O-plate gray scale  
5 compensation.

6  
7 Figure 8 is an illustration of the viewer's perspective relative to the average director orientation of a  
8 liquid crystal.

9  
10 Figures 9 show calculated brightness vs. voltage electro-optic curves for a normally white, twisted  
11 nematic liquid crystal display, at a variety of horizontal viewing directions having the benefit of O-plate  
12 compensation in accordance with the invention.

13  
14 Figures 10 show calculated brightness versus voltage electro-optic curves for a normally white,  
15 twisted nematic liquid crystal display, at a variety of vertical viewing directions having the benefit of O-  
16 plate compensation in accordance with the invention.

17  
18 Figure 11 is a cross-sectional view of an illustrative liquid crystal display in accordance with the  
19 invention

20  
21 Figure 12 shows an expanded cross-sectional view of a monolithic compensator device in  
22 accordance with the invention.

23  
24 **5. DETAILED DESCRIPTION OF A SPECIFIC EMBODIMENT**

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26 One illustrative embodiment of the invention is described below as it might be implemented using  
27 thin film techniques to create a monolithic compensator device. In the interest of clarity, not all features of

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1 an actual implementation are described in this specification. It will of course be appreciated that in the  
2 development of any such actual implementation (as in any development project), numerous implementation-  
3 specific decisions must be made to achieve the developers' specific goals and subgoals, such as compliance  
4 with system- and business-related constraints, which will vary from one implementation to another.  
5 Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but  
6 would nevertheless be a routine undertaking of device engineering for those of ordinary skill having the  
7 benefit of this disclosure.

## 8 9 5.1 Overview of Liquid Crystal Display Structure

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11 Figure 11 shows an illustrative liquid crystal display 1100 in accordance with the invention. The  
12 liquid crystal display 1100 includes a conventional polarizer 300, a conventional analyzer 305 that has a  
13 transmission axis perpendicular to the transmission axis of the polarizer 300, a conventional liquid crystal  
14 cell 1105, and a novel monolithic compensator 1110. As is well known to those of ordinary skill, the liquid  
15 crystal cell 1105 typically is defined by two substrate walls 1115, between which is a layer of liquid crystal  
16 material 1120. Of course, an actual display would also include electrodes to receive a video display signal  
17 and perhaps other elements such color filters (not shown).

## 18 19 5.2 Monolithic Compensator Structure

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21 Disposed between the polarizer layer 300 and the analyzer layer 305 is a monolithic compensator  
22 1110 in accordance with the invention. A typical monolithic compensator 1110 is shown in expanded view  
23 in Figure 12. The monolithic compensator includes a substrate 1200, which may be of any convenient  
24 transparent material such as glass or plastic. The substrate 1200 may be a separate component specifically  
25 designed to function as a compensator substrate. Alternatively, the substrate 1200 may be one of the  
26 substrates used as a wall 1115 of the liquid crystal cell 1105, the polarizer layer 300, or the analyzer layer  
27 305. It will be apparent to those of ordinary skill having the benefit of this disclosure that multiple

1 instances of the substrate 1200 may be formed on any or all of these components.

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3 The illustrative monolithic compensator 1110 includes a positively birefringent O-plate thin-film  
4 compensator layer 1210 with a suitable conventional surface treatment 1205 between that layer and the  
5 monolithic compensator 1110. The surface treatment 1205 provides for the desired orientation of the O-  
6 plate compensator layer and further can act as a layer to promote adhesion of the O-plate thin-film  
7 compensator layer to the substrate 1200.

8  
9 The illustrative monolithic compensator 1110 also includes one or more additional thin-film  
10 compensator layers. The additional layer(s) may comprise, e.g., (i) another positively birefringent O-plate  
11 compensator layer similar to but having a different optical axis orientation than the O-plate compensator  
12 layer 1210; (ii) a positively birefringent A-plate compensator layer 1220, (iii) a negatively birefringent A-  
13 plate compensator layer, not shown, and (iv) a negatively birefringent C-plate compensator layer 1230. It  
14 will be appreciated by those of ordinary skill that the illustrative monolithic compensator 1110 may also  
15 include suitable conventional surface treatments between any two layers such as the surface treatments  
16 1205, 1215, and 1225.

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18 The arrangement of components in the monolithic compensator 1110 may take a wide variety of  
19 forms, and the different thin-film compensator layers need not be arranged in any particular order. See, for  
20 example, the various component arrangements summarized in Table 1 above. The invention is not limited  
21 to the particular arrangement shown as monolithic compensator 1110 in Figure 12.

### 22 23 5.3 Manufacture of the Monolithic Compensator

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25 A manufacturing process for fabricating a monolithic compensator is discussed with reference to  
26 the illustrative monolithic compensator 1110. It will be understood that similar processes may be used for  
27 the various thin-film layers in whatever order they are arranged on the substrate 1200.



1 The O-plate thin-film compensator layer 1210 may be deposited on the substrate 1200 (or on any  
2 other thin-film layers previously deposited, as discussed above) by any convenient method, e.g., a solvent-  
3 casting process. Two examples of deposition processes for O-plate thin-film compensator layers are taught  
4 in the previously cited co-pending U.S. patent applications. It should be noted that the term "deposition"  
5 here is intended to be distinct from lamination, in which pre-formed compensator layers are glued or  
6 otherwise bonded to the substrate 1200.

7  
8 The positively birefringent A-plate thin-film compensator layer 1220 may be deposited via any  
9 convenient process, e.g., a solvent casting process. In an illustrative embodiment, an alignment layer 1215  
10 is produced by coating a surface of an O-plate compensator layer 1210 (acting as a substrate to a  
11 subsequent A-plate layer 1220) with a polyimide material that produces a nearly zero liquid crystal pretilt  
12 angle. A thin film of the liquid crystal monomer is formed on the alignment layer 1215 by the use of spin  
13 coating from a solution of the liquid crystal material in a solvent. Other methods of producing thin films of  
14 organic liquid crystal material include dip and slot-die coating. The concentration of the liquid crystal  
15 monomer, a diacrylate material that has an intrinsic nematic/air tilt angle of nearly zero degrees, is about  
16 10%. The solvent is monochlorobenzene. The coating solution also includes approximately 0.05%  
17 Irgacure-651, a photoinitiator. As would be obvious to those skilled in the art, many other different  
18 materials could be used for the liquid crystal monomer, Irgacure-651 and monochlorobenzene.

19  
20 After the liquid crystal film is produced, the solvent is evaporated off and the temperature of the  
21 liquid crystal layer is adjusted to produce a thin film of the liquid crystal material in the nematic phase.  
22 Next, the liquid crystal film is illuminated with ultraviolet light (actinic radiation) at a wavelength of  
23 approximately 360 nanometers (nm) to achieve a total exposure that is sufficient to polymerize the  
24 monomer to a polymeric film in which the order of the liquid crystal phase is preserved, typically 4-10  
25 J/cm<sup>2</sup>. The result of this process is a thin film of liquid crystal polymer that is positively birefringent and  
26 has a symmetry axis that is oriented substantially in the plane of the film, hence, an A-plate 1220.

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1           The C-plate thin-film compensator layer of 1230 may be deposited via any convenient process,  
2 e.g., a solvent casting process. One example of a deposition process for C-plate thin-film compensator  
3 layers is taught in allowed application Serial No. 08/072,137, filed June 4, 1993, assigned to the University  
4 of Akron and exclusively licensed to the assignee of this application. Another process for negatively  
5 birefringent C-plate thin-film compensator layer deposition is described in Yeh et al., assigned to the  
6 assignee of this application.

7  
8           In many circumstances some of the thin-film layers may not require surface treatments. For  
9 example, a polyimide thin-film negative C-plate compensator layer does not require the use of an alignment  
10 layer, and further may be used itself as an alignment layer for subsequent A-plate or O-plate thin-film  
11 layers when the A-plate or O-plate layers are formed by solvent casting of liquid crystal material. (It will  
12 be apparent to those of ordinary skill that in such a case the polyimide thin-film C-plate compensator layer  
13 would require a conventional rubbing operation.)

#### 14 15 5.4 Advantages of the Monolithic Compensator

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17           The benefits of the monolithic compensator illustrated in Figure 12 include, for example, reduction  
18 in parts count (and thus in parts cost); reduced assembly costs; and reduced weight/thickness of a display  
19 using a monolithic compensator in accordance with the invention. The reduced display weight can be  
20 especially important in, e.g., avionics and personal-computer applications, in which savings of a few  
21 ounces can be significant.

22  
23           The monolithic compensator also contributes to improved reliability and yield of the liquid crystal  
24 display assembly process. In addition, as noted above, the compensator thin-film layers can be laid down  
25 directly on the liquid crystal glass, i.e., on the wall of the liquid crystal cell 1105. Significant weight and  
26 cost reductions are thus achieved by eliminating a separate compensator substrate.

22

1 Using deposition techniques to lay down a plurality of thin-film compensator layers also reduces  
2 the number of adhesive layers needed to keep the various compensator elements together in the display.  
3 This, in turn, can increase display reliability by reducing the problems associated with adhesive failure.

4  
5 By reducing the number of glass substrates used in a liquid crystal display, the potentially  
6 annoying reflectivity of the display is concomitantly reduced. A similar benefit accrues from the  
7 elimination of adhesive layers discussed above.

## 8 9 6. BIBLIOGRAPHY

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22 It will be appreciated by those of ordinary skill having the benefit of this disclosure that numerous  
23 variations from the foregoing illustration will be possible without departing from the inventive concept  
24 described herein. Accordingly, it is the claims set forth below, and not merely the foregoing illustrative  
25 embodiments, which are intended to define the exclusive rights claimed in this application program.